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TITLE: EVALUATION OF STEELS FOR SENSITIVITY TO HYDROGEN INDUCED CRACKING IN THE REHEAT HEAT AFFECTED ZONE (PERD)

FINAL REPORT

BY

B.A. GRAVILLE

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Complete details of the technical results of the program are contained in the following technical reports:

#148/1 Effect of prior heat treatment on bend test behaviour.

#148/2 Examination of bend specimens to determine causes of scatter.

#148/3 Procedure for welded hydrogen embrittlement slow bend tests.

#148/4 High strength pipeline steels: Summary of strengthening and manufacturing options and implications concerning chemical compositions.

#148/5 Causes of scatter in notched bend tests.

#148/6 Preliminary finite element analysis of the bend test.

#148/7 Bend Test Models

#148/8 Bend tests on experimental steels

#148/9 Laboratory simulation of cracking in a repair weld

#148/10 Bend tests on commercial steels

#148/11 Preliminary analysis of bend test results

#148/12 Portability of the slow bend test

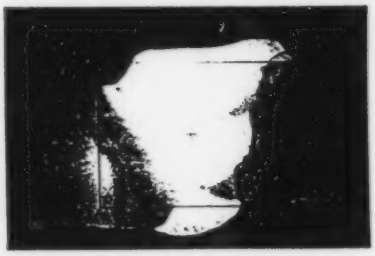
#148/13 Effects of phosphorus and analysis of bend test results

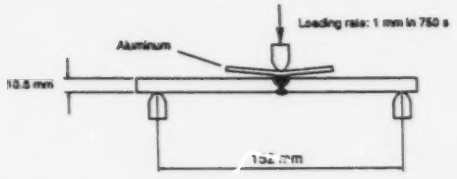
#148/14 Additional tests on the effects of strength

HYDROGEN CRACKING IN THE REHEATED HEAT AFFECTED ZONE OF PIPELINE STEELS

Executive summary

Cracking in repair welds and tie-in welds made with cellulosic electrodes can occur in the heat affected zone at the root. It is believed it results from local bending of the weld caused by weld contraction around the pipe circumference resulting in a high transverse strain in the root heat affected zone. Hydrogen diffuses from the fill passes. The on-set of cracking may be delayed well after welding is completed. This type of cracking has been reproduced in the laboratory on a full pipe section.



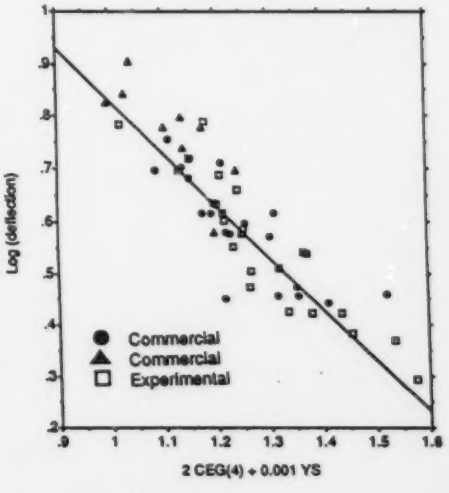


Loading arrangement

To evaluate the sensitivity of various steels to this problem a simple bend test has been used. The sample is welded with E8010G electrodes and loaded very slowly to maximize the effects of hydrogen embrittlement. The deflection to failure is measured.

Tests on a single steel heat treated to give various base metal strength levels showed that with a lower strength a greater deflection was obtained in the bend test. The lower sensitivity to cracking with a lower strength steel was explained by the local yielding of the base metal prior to reaching the critical strain necessary at the heat affected zone to cause cracking. The mechanics of the bend test have been modelled in a simple theoretical model and using finite element analysis. For practical purposes the strength effect can be related simply to the base metal yield strength.

Designed experiments using specially made steels have been used to determine the effects of composition. Carbon has the greatest effect and the macroalloy elements Mn, Mo, Cr and, to a smaller extent, Ni also contribute. No effect was found for P, Nb, S. Nitrogen, over the normal range encountered in practice, was not thought to contribute significantly. The effects of composition could be represented by a carbon equivalent (C + Mn/8 + Mo/8 + Cr/5 + Ni/41) similar to the IIW CE. Other formulae, such as Pcm or CEN, were not good indicators of susceptibility.



The composition and strength effects have been combined into a single parameter which predicted susceptibility well for a wide range of experimental and commercial steels tested.

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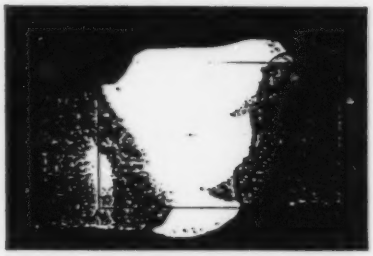
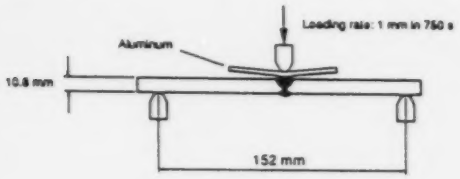
Brian A. Graville. *Graville Associates Inc.* P.O.Box 225 Georgetown, Ontario L7G 4Y5 Canada. Tel (416)-873-1739 FAX (416)-873-0466

FISSURATION PAR L'HYDROGÈNE DANS LA ZONE THERMIQUEMENT AFFECTÉE RÉCHAUFFÉE DES SOUDURES D'ACIERS DE PIPELINES.

Sommaire

La fissuration dans les soudures de réparation et les soudures de jonction faites avec des électrodes cellulosiques peut se produire dans la zone thermiquement affecté, au niveau de la racine. On croit qu'elle provient d'une flexion locale de la soudure causée par sa contraction le long de la circonférence du tuyau qui cause de fortes contraintes transversales dans la zone thermiquement affectée, à la racine. L'hydrogène diffuse à partir des passes de remplissage. L'apparition de la fissuration peut être différée bien apres la fin de l'opération de soudage. Ce type de fissuration a été reproduit en laboratoire sur une section entiére de tuyau.



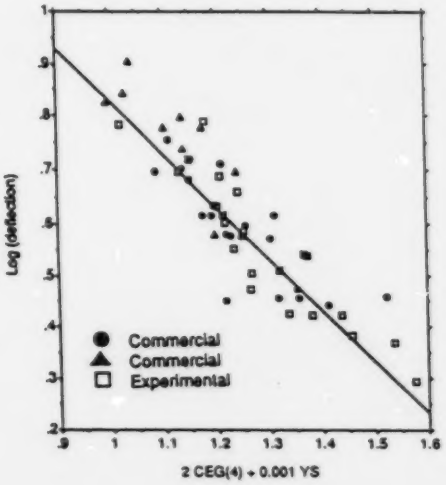


Loading arrangement

Pour évaluer la sensibilité de différents aciers à ce problème on a utilisé un simple essai de pliage. Les échantillons ont été soudés avec des électrodes enrobées E8010G et mis en charge très lentement pour augmenter les effets de fragilisation par l'hydrogène. On a mesuré la déflexion au moment de la cassure.

Les essais de pliage des métaux de base en acier courant mais traités thermiquement pour leur conférer valeurs de résistance ont montré que les plus grandes valeurs de déflexion étaient obtenues avec les plus faibles valeurs de résistance. On a expliqué la plus petite sensibilité à la fissuration des aciers à plus faible résistance par l'écoulement plastique local du métal de base à un niveau inférieur à la contrainte critique qui cause la fissuration dans la zone thermiquement affectée. Les effets mécaniques de l'essai de pliage ont fait l'objet d'un modèle théorique simple, basé sur l'analyse avec les éléments finis. D'un point de vue practique, l'effet de la résistance du métal de base a pu être relié simplement à sa limite d'élasticité.

Des aciers spécialement élaborés pour ces essais expérimentaux ont été testés pour déterminer l'influence de leur composition chimique. Le carbone a le plus grand effet de même que les éléments macroalliés Mn, Mo et Cr; à un degré moindre, le Ni aussi à une influence. On n'a déterminé aucune influence de P, S et Nb. L'azote, dans les plages de concentration recontrées en practique, n'a pas paru jouer un rôle significatif. On a pu représenter les effets de la composition chimique par une formule de carbone équivalent (C+Mn/8+Mo/8+Cr/5+Ni/41) semblable à celle du CE de l'IIS. D'autres formules comme le Pcm ou le CEN ne se sont pas avérées êtres de bons indices de tendance à la fissuration.



Les effets de la composition et de la résistance ont été combinés en un seul parametre qui a bien évalué la tendance à la fissuration du vaste échantillon d'aciers expérimentaux et commerciaux testés.

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Brian A. Graville. *Graville Associates Inc.* P.O.Box 225 Georgetown, Ontario L7G 4Y5 Canada. Tel (416)-873-1739 FAX (416)-873-0466

HYDROGEN CRACKING IN THE REHEATED HEAT AFFECTED ZONE OF PIPELINE GIRTH WELDS

By B.A.Graville

Graville Associates Inc. P.O.Box 225, Georgetown, Ontario L7G 4Y5

INTRODUCTION

When hydrogen cracking occurs in welds it usually initiates in the as-formed heat affected zone (HAZ), often where the coarse grained HAZ has been hardened by a fast cooling rate. In some circumstances, however, cracking may occur in a heat affected zone that has been reheated and softened by subsequent passes. In one example cracking occurred in repair welds and tie-in welds on a large diameter (1067 mm) pipeline in grade 483 (X70) steel welded with cellulosic electrodes (E8010G). A general description of the cracking has been given previously[1] and some of the important features are noted. Cracking appeared to occur well after completion of the tie-in or repair weld when several passes had been deposited. Thus it was believed the crack initiated in a heat affected zone that had been reheated by subsequent passes. Second, although field welding was being carried out in cold weather (-20° to -30°C), the use of preheats up to 200°C did not appear to relieve the problem. Only an extended postheat of a few hours successfully avoided cracking. Third, cracking appeared to occur under the influence of self-induced strains from welding, and external sources of stress, such as lifting, did not appear to be necessary. In addition, the hardness of the HAZ was in the range 230 - 290 Hv which was well below the values usually associated with hydrogen cracking.

A typical section of a cracked repair weld is shown in Figure.1. Initiation occurred at the root pass toe (or original GMAW bead in the case of a repair) and propagated through the reheated HAZ.

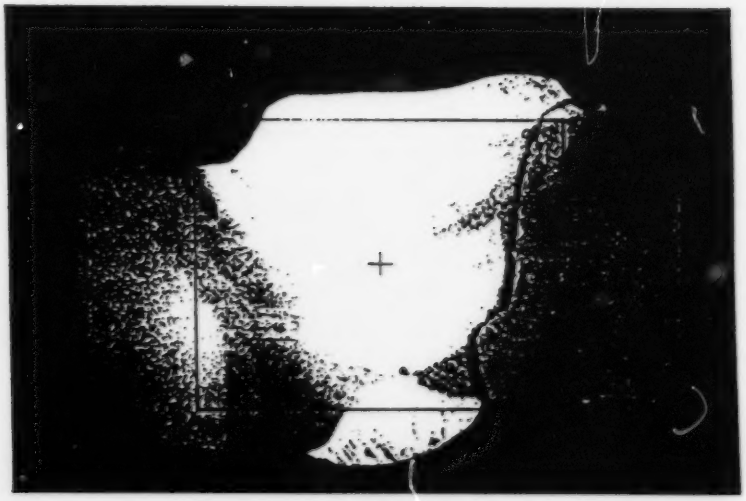

Figure 1 - Example of crack initiating in the reheated heat affected zone of a repair weld.

It was believed that a high transverse root strain from the contracting circumferential weld, coupled with hydrogen diffusing from the weld metal, caused the cracks. The stress concentration formed by the high-low offset of the pipe ends undoubtedly contributed to the local strain in the HAZ, but since cracking was also observed in repair welds with very little high-low (0.5 mm) an excessive high-low did not appear to be a prerequisite for cracking.

The research program reported here was aimed at identifying the major factors contributing to cracking with particular emphasis on the steel composition.

SIMULATION TEST

In order to confirm some of the main assumptions in the model of cracking, a full-scale simulation repair weld was carried out in the laboratory on a 9 m length of pipe. The pipe was 1067 mm diameter and 10.6 mm wall thickness. The material used had been associated with cracking problems in the field and was therefore considered susceptible. The composition of the steel is given in Table I. In order to avoid any external stresses from clamps, the initial weld was made by grooving the pipe circumference then filling the groove using GMAW. A short section (500 mm) representing the repair was then ground out, a small degree of high-low introduced, then the repair weld made using E8010G electrodes. The welding procedure followed as closely as possible a typical field procedure including a preheat of 150°C. Ambient temperature was 20°C.

Table I - Composition of steel used in the simulation test (wt %)

C	Mn	S	P	Si	Nb	V	Cu	Ni	Cr	Mo	ASA	N	Ti	Sn
0.093	1.95	0.004	0.018	0.33	0.072	0.0	0.36	0.1	0.07	0.201	0.024	0.013	0.015	0.021

Following welding, the inside of the pipe was monitored to detect the onset of cracking using the magnetic particle inspection method. This was selected so as to give roughly the same sensitivity as the inspection methods used in the field. In addition, overall deflection of the weld region relative to the pipe was measured. Constant monitoring up to 23 hours showed no evidence of any cracks. At 25 h an indication 40 mm long appeared at the root toe on the pipe inside towards one end of the repair weld. Sectioning showed a large crack through the HAZ of the root having all the same characteristics as the cracks observed from the field. A second test simulating a tie-in weld showed no cracks.

The results of the repair weld simulation test confirmed that delayed cracking could occur in the reheated HAZ of the weld, initiating well after completion of the weld. Very low ambient temperatures were not necessary for cracking to occur. Cracking could result from the strains induced from weld contraction alone and external sources were not necessary. The radial deflection of the pipe at the weld was about 3 mm. These results provided direct evidence supporting the cracking model proposed to explain the field problems.

Since, according to this model, hydrogen must diffuse a significant distance from the fill passes

to the site of initiation, cracking could be considerably delayed. Finite difference modelling suggests that at low temperatures a high hydrogen content at the root could be maintained many days after welding[1]. Evidence from the field suggested that at ambient temperatures of about -20°C cracking occurred many days after welding.

BEND TEST

In order to study the factors influencing hydrogen cracking in the reheated HAZ, a simple laboratory test was devised to provide a measure of the susceptibility to cracking. It was recognized that because of the inherent scatter in weld cracking tests, an inexpensive test was needed so that a sufficiently large number of tests could be done to obtain statistical significance. The test is shown in Figure. 2. It comprised a simple bend test on a weld simulating a tie-in. The welding procedure employed a E8010G electrode, a preheat of 150°C and controlled cooling. Specimens were stored at -30°C prior to mechanical testing, and loading was at a very low rate so as to maximize the effects of hydrogen embrittlement. The deflection to maximum load has been used as a convenient measure of sensitivity to cracking. This value would correspond to the extent of bending that the weld or repair weld could sustain in practice as the result of contraction of a given weld. Preliminary tests showed that specimens cracked through the reheated HAZ in the same manner as observed in the field with steels suffering cracking in the field having lower deflections in the bend test. Deflections to failure in the susceptible steels were typically 2 to 3 mm, being of the same order as the radial deflection

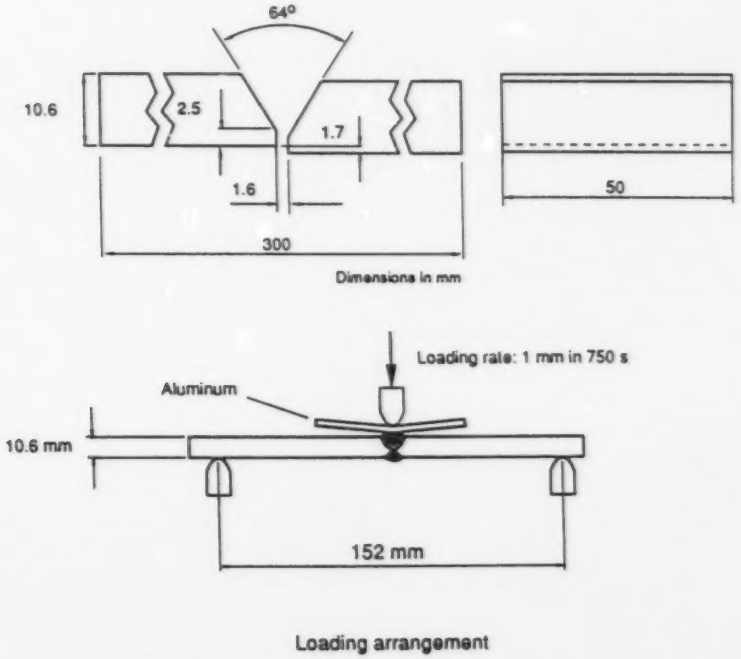

Figure 2 - Slow bend test used for assessing the sensitivity to hydrogen cracking

noted in the simulation test. In addition, the dramatic increase in deflection resulting from aging the specimens at 150°C for 3 h confirmed the role of hydrogen in the cracking process.

Initial tests showed quite a bit of scatter and several specimens were sectioned to determine the source of scatter. Some of this arose from variations in the high-low value and changes to the welding fixture improved this. The remaining inherent scatter resulted from variations in geometry of the root pass because it was deposited manually. Consequently in all work reported here at least two bend tests have been conducted for each steel tested.

A series of tests was carried out to establish that the bend test could be conducted in different laboratories on various machines and obtain the same results. The results showed that comparable results could be obtained on different machines if the following points were addressed.

First, the loading rate should not be changed for machines of different compliance. Although a difference in compliance might change the time required for the load to reach a given value, the loading rate that affects hydrogen embrittlement is that just before fracture after a plastic hinge is formed and where machine compliance has little effect. The loading rate prior to this point has no effect[2]. Thus the standard loading rate of 1 mm in 750 s should be used for any machine.

Second, the deflection should be measured at the load point preferably with a separate gauge on the specimen. If the actuator or cross head deflection is used then it requires a calibration to account for machine compliance.

Third, good four point seating of the specimen in the testing machine is required. Poor seating results in a lower apparent modulus for the specimen and a higher deflection to failure. Poor seating can occur with specimens cut from pipe samples and these require careful clamping during welding and checking prior to testing.

EFFECT OF BASE METAL PARAMETERS

A number of base metal parameters could affect the sensitivity to cracking in the bend test including the yield and ultimate strengths, composition, and base metal microstructure. To identify these effects a series of tests was carried out on a single heat of steel heat treated to provide various strengths and base metal microstructures. The composition of the steel is shown in Table I, and material was tested in the as-received, stress relieved, normalized, and quenched and tempered condition. The last heat treatment was designed to produce the same strength level as the as-received material but with a substantially different microstructure. A second steel was also tested in two conditions representing different microstructures but the same strength. Results of bend tests and tensile tests on these are given in Table II which shows that the lower strength normalized condition results in a significantly increased deflection to failure in the bend test. However, changing the microstructure while keeping the strength constant did not affect the bend test behaviour as shown by the similar results for the quenched and tempered and as-received conditions.

From this it was concluded that, at least for the materials tested, base metal original microstructure did not affect the bend performance, but strength did. It thus appeared that the effect

of base metal strength was a mechanical one, increasing the local strain at the point of crack initiation. Further confirmation of this was obtained by conducting a few modified bend tests involving partial joint penetration in which the design of the test prevented gross yielding of the base metal prior to cracking, thus removing any effect of base metal strength. Tests were conducted on the steel given in Table I in the as-received and normalized condition. Results given in Table II show no significant difference in deflection.

Table II - Results of tests on heat treated steels

Condition	Yield (MPa)	UTS (MPa)	Deflection (mm, average of 2 or 3)
Steel 1			
As-received	656	771	2.78
SR 650°C 1 h	NA	NA	2.97
N 900°C 0.5 h	356	692	5.72
Q & T	765	794	2.88
Steel 2 (MB16)			
As-received	Hardness 242 Hv		1.97
N & T	Hardness 241 Hv		1.90
Modified tests (partial joint penetration) steel 1			
As-received	656	771	1.91
N 900°C 0.5 h	356	692	2.06

BEND MODELS

A number of models of the bend test were developed in order to quantify the effect of base metal strength on the bend test performance. The basic assumption was that cracking initiated when a critical local strain was reached in the HAZ of the root pass. Analysis of the mechanics of the test would then provide a relation among the local strain, the deflection to failure, and the mechanical properties of the various regions in the weld and base metal. A finite element analysis (FEA) was carried out using the model shown in Figure. 3. The numerical model used a large displacement, elasto-plastic formulation. Measured mechanical properties were assigned to the weld metal and the base metal, but the properties of the HAZ were estimated using hardness data. The data of Akselsen et al[3] showed that the work hardening rate of equiaxed structures in the HAZ was quite high and the value $n = 0.12$ was used in the present. Of significance is the fact that a HAZ with the same hardness as the base metal might have a lower yield strength if it has been reheated to produce an equiaxed structure.

Seven FEA runs were performed covering base metal strengths corresponding to the as-received, normalized, and an intermediate condition of the steel used in the tests previously discussed. The intermediate condition simply used the average of the as-received and normalized strengths. Two levels of weld metal strength were included, one in which an estimate of the root pass strength was used for all weld metal (FEM2) and the other in which the bulk properties from tensile tests were used for all weld metal (FEM1). The results of the FEA are shown in terms of local HAZ total strain versus load point deflection in Figure. 4. The initial part of the curves show elastic

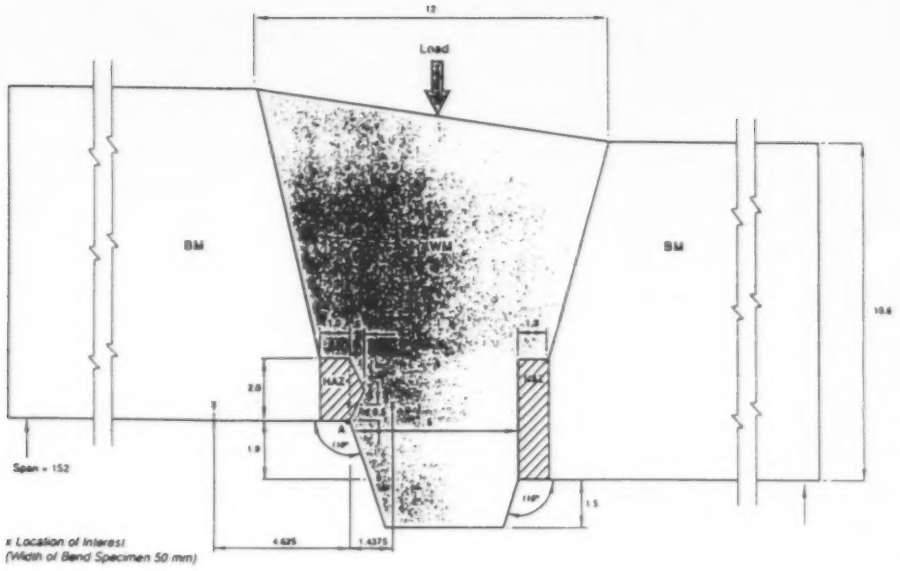

Figure 3 - Geometry of the FEA model of the bend test

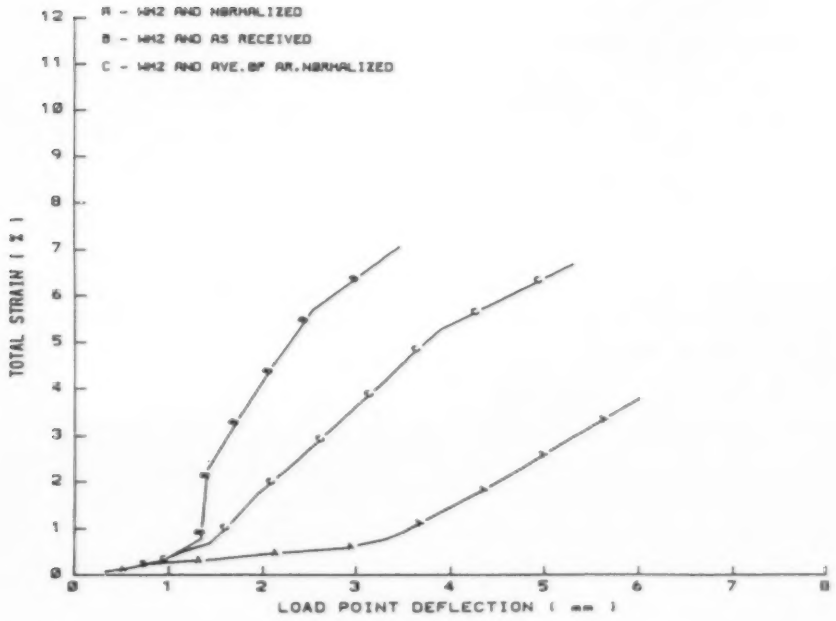

Figure 4 - Results of finite element analysis of bend test showing local strain against deflection

behaviour after which there is a marked difference in behaviour dependent on the base metal strength. For the lower strength normalized condition, deflection increases substantially without significant increase in local strain as the base metal yields and allows the specimen to deform. Finally the local strain starts increasing. In the as-received condition strain increases immediately with increasing deflection after the elastic region.

A simpler model of the bend test was also developed so that it could be run quickly to account for strength effects in the large number of bend tests described in a later section of this paper. In the simple model, the specimen was divided into rectangular elements and the bending moment carried by each element calculated assuming elastic-plastic behaviour with work hardening and assuming plane sections remained plane. Total specimen behaviour was found by summing contributions to deflection of each element. An arbitrary stress concentration factor of 4.5 was applied to the strain in the HAZ to account for the high-low. Results from this model in terms of load/deflection behaviour are compared with measured values in Figure. 5 and agreement is very good. Local HAZ strain versus deflection is shown in Figure. 6 and the overall shape of the curves is similar to those obtained from FEA. When these models are applied to the deflection data obtained for the heat treated steel the local strain values given in Table III are obtained. These values are for a given weld metal (E8010G). The values of local strain at maximum load are closer than the deflections in all cases regardless of the base metal strength, thus supporting the hypothesis that cracking initiates at a critical local strain value for a given HAZ. The values in Table III also provide reasonable support for the simple model as a means of accounting for base metal strength in the bend test.

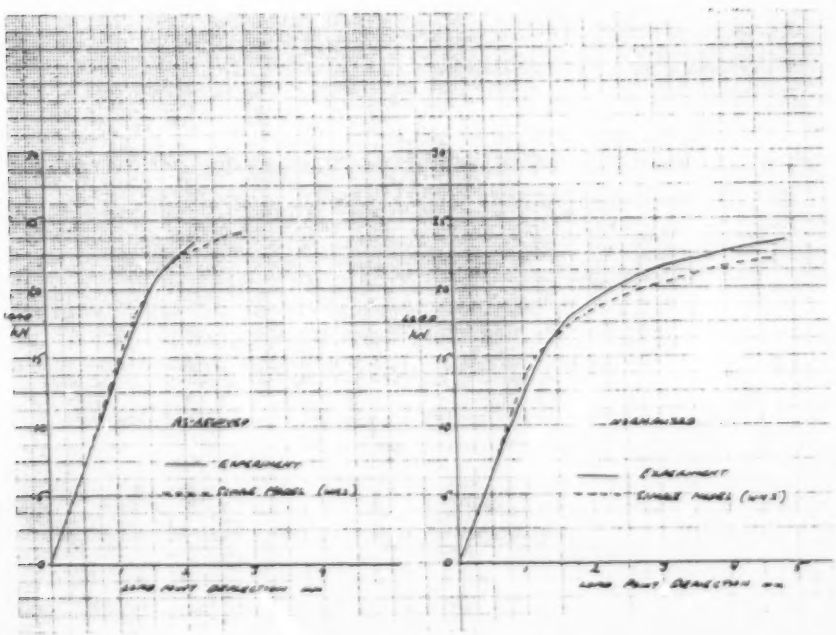

Figure 5 - Load/deflection curves predicted by the simple model compared with measured values

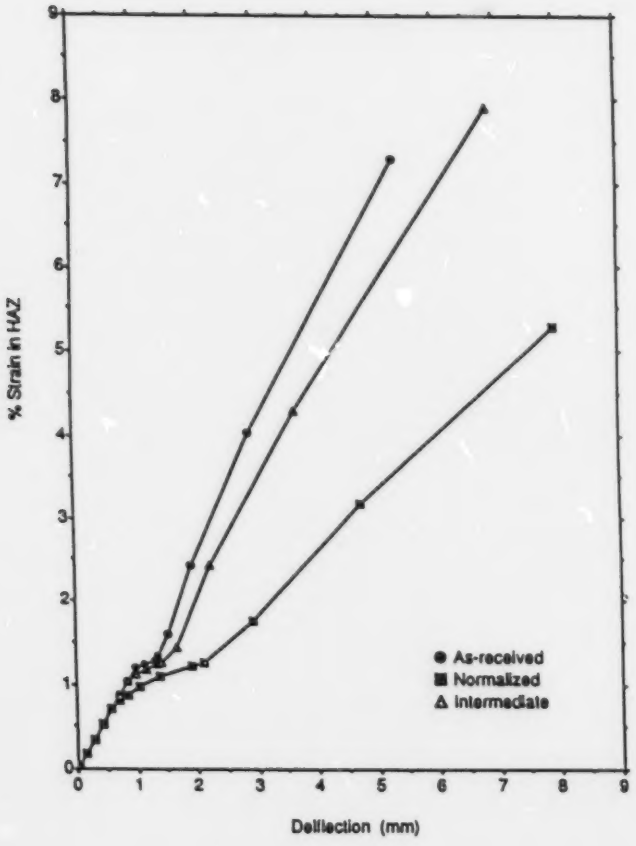

Figure 6 - Local HAZ strain as a function of deflection as predicted by the simple model

Table III - Local HAZ strain for heat treated steels

Condition	Deflection (mm) (adjusted for compliance)	HAZ Strain % FEM 1	SM 1	FEM 2	SM 2
As-received	2.3	4.0	1.8	5.2	3.8
Q & T	2.4	5.1	1.8		3.9
Normalized	5.3	4.6	2.9	3.0	4.7

For practical purposes an even simpler expression relating local strain, deflection, and mechanical properties was sought. This was done by generating a large number of data points for fictitious steels using the simple model. The mechanical properties of the steels covered a wide range of yield strengths including most types of commercial pipeline steels likely to be encountered. From this, simple relations among the parameters of interest were sought using regression analysis which led to the following expression:

$$\log(\varepsilon) = -0.714 + 1.268 \log(\Delta) + 0.0013\ YS \qquad (1)$$

where ε is the local strain, Δ the deflection, and YS the base metal yield strength. The R-value for this regression was 0.959 with 52 data points indicating it to be a useful approximation for practical use. This expression is found useful later in combination with an expression for the effects of composition.

EFFECTS OF COMPOSITION

Two methods were used to quantify the effects of composition on sensitivity to hydrogen cracking in the reheated HAZ. First, a large database of bend tests on commercial steels (two tests for each steel) including those that had experienced cracking in the field was established. Steels covered a wide range of compositions and strengths from grade X65 to X80. Strength data was obtained by laboratory tensile tests on many of these steels. Second, specific compositional effects were studied in designed experiments using specially made laboratory heats. Steels were air melted in 45 kg heats and rolled to approximately 12 mm thick to allow for machining the final specimens of 10.6 mm thickness. In the first series, sixteen experimental steels were made having the compositions and tensile properties shown in Table IV. The experiment was designed to test the main effects of C, Mn, Mo, Cu, Cr, Ni, N, and the interactions, C×Cr, C×Mn, C×Mo. Three standard slow bend tests were carried out for each of these steels and the results are given in Table V.

Table IV - Compositions and tensile properties of first series of experimental steels

Code	C	Mn	P	S	Si	Nb	V	Cu	Ni	Cr	Mo	Al	N	Ti	YS MPA	UTS MPa
MB1	0.05	1.6	0.012	0.0056	0.2	0.052	0	0.1	0.01	0.15	0.13	0.036	0.0036	0.008	586	776
MB2	0.047	1.7	0.01	0.0048	0.2	0.063	0	0.43	1.2	0.16	0.48	0.035	0.004	0.008	606	819
MB3	0.048	1.6	0.01	0.0077	0.22	0.08	0	0.4	0.9	0.35	0.16	0.041		0.01	546	780
MB4	0.057	1.4	0.008	0.007	0.17	0.052	0	0.12	0.05	0.32	0.52	0.032	0.0155	0.008	529	760
MB5	0.055	1.8	0.011	0.0064	0.17	0.055	0	0.11	1.2	0.15	0.16	0.035	0.0178	0.014	514	739
MB6	0.048	1.9	0.011	0.0038	0.18	0.059	0	0.46	0.02	0.16	0.48	0.046	0.0152	0.009	507	737
MB7	0.058	2	0.011	0.0064	0.19	0.043	0	0.39	0.03	0.28	0.15	0.03	0.0049	0.009	477	725
MB8	0.061	2	0.01	0.006	0.19	0.045	0	0.1	1.2	0.31	0.48	0.03	0.0051	0.011	613	877
MB9	0.085	1.4	0.011	0.0052	0.18	0.038	0	0.39	0.03	0.15	0.13	0.03	0.0154	0.009	595	887
MB10	0.094	1.4	0.01	0.006	0.18	0.053	0	0.09	1.1	0.16	0.49	0.036	0.0184	0.0095	558	851
MB11	0.094	1.5	0.01	0.0056	0.18	0.052	0	0.1	1.1	0.3	0.15	0.032	0.0043	0.0083	598	666
MB12	0.1	1.5	0.009	0.0054	0.21	0.051	0	0.41	0.03	0.3	0.5	0.033	0.0043	0.0083	559	844
MB13	0.094	2	0.012	0.0047	0.17	0.053	0	0.38	1.2	0.16	0.14	0.034	0.0037	0.008	613	912
MB14	0.091	2.1	0.01	0.006	0.19	0.058	0	0.1	0.03	0.16	0.49	0.037	0.0047	0.008	561	853
MB15	0.089	1.9	0.013	0.0049	0.19	0.054	0	0.09	0.02	0.31	0.14	0.035	0.0145	0.008	437	751
MB16	0.099	1.9	0.011	0.0047	0.22	0.054	0	0.39	1.2	0.29	0.48	0.035	0.0141	0.008	607	778

Table V - Results of bend tests on first series of experimental steels

Steel	MB1	MB2	MB3	MB4	MB5	MB6	MB7	MB8
Deflection*	6.15	3.48	3.2	3.85	3.57	2.98	4.58	2.35
Steel	**MB9**	**MB10**	**MB11**	**MB12**	**MB13**	**MB14**	**MB15**	**MB16**
Deflection*	4.88	2.67	3.45	2.65	2.65	2.43	3.77	1.97

* average of three tests (mm)

A second series of experimental steels was made to investigate the main effects of C, P, Nb, S, and the interactions C×P and C×S. Compositions and tensile properties are shown in Table VI and results of bend tests are given in Table VII. In both series of experimental steels an attempt was made to obtain constant strength in all the steels in order to eliminate the strength effect described earlier. This was done by modifying the finish rolling temperature or by further heat treatment selected on the basis of composition. This was only partially successful and, although many of the steels had a similar strength, the range of compositions was too high to achieve a constant strength for all steels.

Table VI - Compositions and tensile properties of second series of experimental steels

Code	C	Mn	P	S	Si	Nb	V	Cu	Ni	Cr	Mo	Al	N	Ti	YS(0.5)	TS
															MPa	MPa
148/P1	0.043	1.3	0.011	0.0035	0.17	0.029	0	0.11	0	0.14	0.19	0.021	0.00	0.007	505.4	663.3
148/P2	0.049	1.5	0.011	0.0087	0.18	0.079	0	0.11	0	0.14	0.2	0.032	0.0038	0.007	550.2	742.6
148/P3	0.1	1.4	0.033	0.01	0.23	0.03	0	0.08	0	0.15	0.18	0.029	0.004	0.01	557.1	851.5
148/P4	0.1	1.6	0.026	0.0031	0.29	0.1	0	0.11	0	0.14	0.21	0.03	0.0038	0.009	610.2	663.3
148/P5	0.061	1.6	0.026	0.003	0.21	0.035	0	0.11	0	0.14	0.2	0.026	0.004	0.007	587.5	812.2
148/P6	0.055	1.4	0.028	0.0088	0.17	0.076	0	0.11	0	0.14	0.2	0.025	0.004	0.006	584.7	667.4
148/P7	0.11	1.4	0.015	0.0086	0.23	0.033	0	0.1	0	0.15	0.2	0.03	0.004	0.011	516.4	686.7
148/P8	0.097	1.6	0.01	0.0032	0.28	0.11	0	0.1	0	0.14	0.21	0.037	0.0036	0.01	500	796.4

Table VII - Results of bend tests on second series of experimental steels

Steel	P1	P2	P3	P4	P5	P6	P7	P8
Deflection*	6.1	4.98	4.15	3.23	4.00	5.25	4.33	4.29

* Average of three tests (mm)

Sections of bend tests were examined and hardness measurements made in the various weld regions. In Figure. 7 the deflection to failure (log form) is plotted against the hardness of the cracked HAZ. There is a rough trend but hardness by itself is clearly not an accurate predictor of bend test behaviour.

ANALYSIS

Statistical analysis was carried out on the results of bend tests from both the experimental steels and the commercial steels. Prior to analysis, checks of correlations among elements were made. For both series of experimental steels no significant correlations existed among the elements of interest, thus confirming the original design of the experiment and suitability of the compositions obtained. For the commercial database, correlations existed among several pairs of elements, the most significant being carbon-manganese and carbon-phosphorus. Thus although the commercial database could be used to test compositional models, it could not be used to derive them. Compositional models were therefore derived from the experimental steels.

Because constant strength was not achieved in the experimental steels, the strength effect was removed by calculating the local critical strain using the simple bend test model. The results of

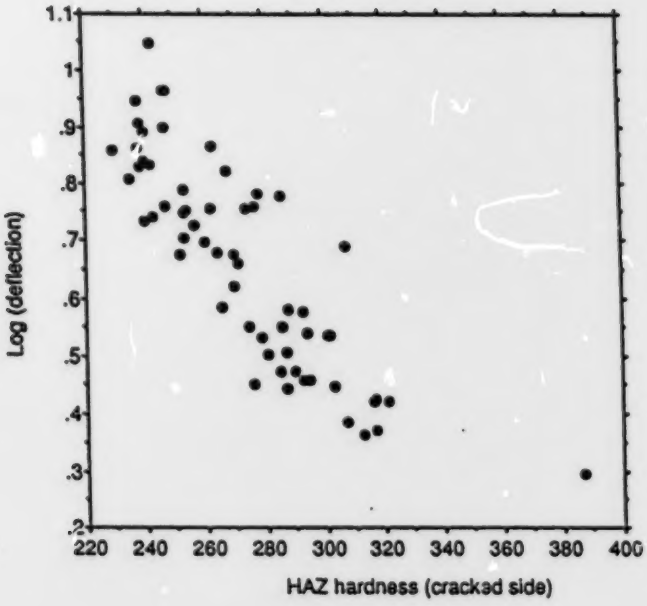

Figure 7 - Relation between deflection in the bend test and HAZ hardness

regression analysis with and without the strength correction are given in Table VIII in the form of coefficients of a linear carbon equivalent. None of the interactions was significant.

In the first series of experimental steels there was a correlation between yield strength and nitrogen (purely statistical and not indicative of a metallurgical cause) which could have resulted in any inaccuracies in the bend model confounding possible nitrogen effects with strength effects. Thus it is very possible that the nitrogen effect observed in Table VIII could have been introduced by the strength correction. When the commercial database was analysed, no nitrogen effect was found. Thus nitrogen was not considered significant and in any event the range likely to be encountered in practice would have a small effect on overall susceptibility.

Table VIII - Results of analyses presented in carbon equivalent form

Dependent variable	C	Mn	Mo	Ni	Cr	N
log (def)	1	1/13	1/6	1/27	NS	NS
log (% strain)	1	1/8	1/8	1/41	1/5	2

NS = not significant

When the second series of experimental steels was analysed, the strong effect of carbon was confirmed. No effect of phosphorus, sulphur, or niobium was found when these elements were added separately to the model, but phosphorus and the phosphorus-sulphur interaction appeared to be significant when included with carbon. There was, however, a correlation between phosphorus and yield strength so the effect could have come from the strength correction. Further analysis was therefore done using the linear yield strength correction expression (1) and the carbon equivalent derived from the first series of steels. No phosphorus effect was found. Furthermore, no phosphorus effect was found when the commercial database was analysed. It was therefore concluded that the major compositional factors affecting the sensitivity to hydrogen cracking in the reheated HAZ were the carbon level and the macroalloy elements (Mn, Cr, Mo, Ni) usually associated with hardenability. There was no reason to attribute effects to any other elements.

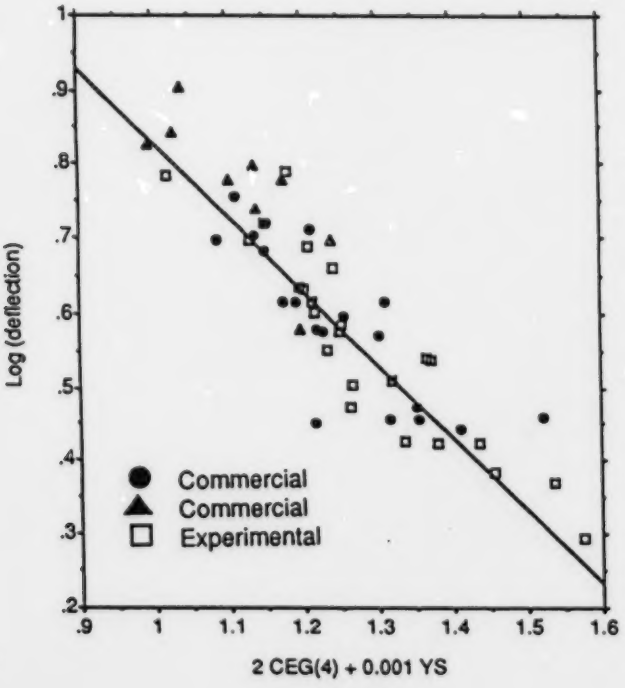

Figure 8 - Relation among bend test deflection, composition and yield strength

DISCUSSION

The results show that the major factors affecting deflection to failure in the bend test are the steel composition and its mechanical properties. These factors can be combined in a simple linear model for practical use. The compositional effects can be expressed in terms of a carbon equivalent CE(4) in the form:

$$\log(\varepsilon) = 1.602 - 2.558\,[\,C + Mn/8 + Cr/5 + Mo/8 + Ni/41\,]$$

Combining this with expression (1) for the effect of strength gives

$$\log(\Delta) = 1.83 - 2.0\,CE(4) - 0.001\,YS \qquad (2)$$

This is shown in Figure. 8 together with all data from tests on both commercial and experimental steels. Each data point is the average of the two bend tests performed on each steel. Good agreement is observed over a wide range of conditions which suggests that expression (2) suitably predicts bend test behaviour for practical purposes.

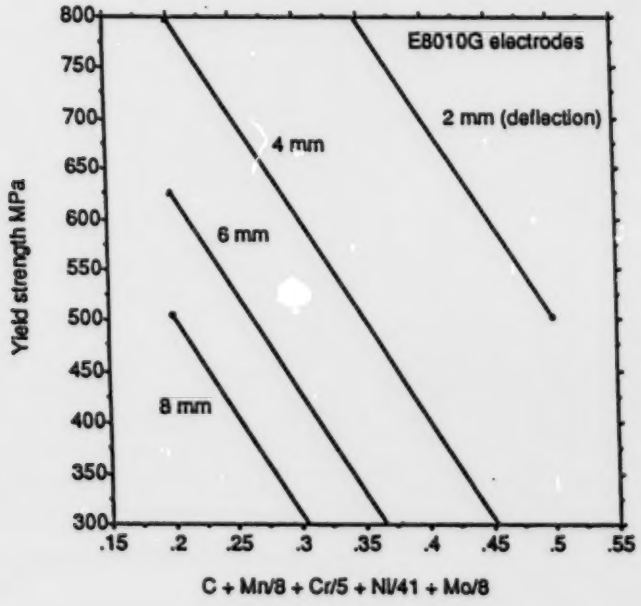

Figure 9 - Yield strength versus CE(4) for given deflections (E8010G weld metal)

Expression (2) is presented in an alternative format in Figure. 9 showing yield strength against CE(4) for given level of deflections in the bend test. This may provide a useful guide to providing yield strength and composition limits to ensure a specific level of performance in the bend test. It is emphasized that the strength model inherent in this expression assumes the use of E8010G weld metal, and the model would change for other levels of weld metal strength.

The factors in the carbon equivalent indicating the magnitude of the effects of various elements are similar to those in the IIW carbon equivalent, and the CE(IIW) may be used equally well in expression (2) with only the constants changed and a negligible sacrifice in accuracy. These carbon equivalents that place weight on the alloy elements describe the compositional effects much better

than the carbon-dominant formulae such as Pcm or CEN. The latter types have proven useful measures of susceptibility to hydrogen cracking in the as-formed HAZ but underestimate the role of alloy elements in the susceptibility of the reheated HAZ. In microstructural studies it has been observed that failure of the reheated HAZ occurs by hydrogen induced cleavage of ferrite grains which in some of the steels examined appeared to be preceded by cracking of MA microphase particles. Thus the main compositional effects may be in determining the size and distribution of the microphases. Details of the microstructural studies are presented elsewhere.

The identification of base metal strength as a significant factor has important implications for controlling the sensitivity to hydrogen cracking in practice, emphasizing the need to specify maximum as well as minimum yield strengths. For higher strength pipe designs particularly, the increased exposure to the risk of cracking provides a strong incentive to use low hydrogen processes where possible. The large strain concentrations that can occur in the HAZ when local bending deformation takes place also have important implications for the credibility of methods for evaluating the significance of root defects.

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HYDROGEN CRACKING IN THE REHEATED HEAT AFFECTED ZONE OF PIPELINE GIRTH WELDS

By B.A.Graville

Graville Associates Inc. P.O.Box 225, Georgetown, Ontario L7G 4Y5

ABSTRACT

A study has been carried out of the factors influencing hydrogen cracking in the reheated heat affected zone of repair welds and tie-in girth welds in pipelines. Sensitivity to cracking has been assessed with a simple bend test carried out under slow loading conditions. Tests on a steel heat treated to obtain different strengths showed that base metal strength had a major effect on the performance in the bend test. This was modelled using both finite element analysis and by a simple semi-analytical model. Tests on two series of experimental steels showed that the major compositional factors influencing sensitivity were the carbon level and the macroalloy elements manganese, molybdenum, chromium, and to a smaller extent, nickel. A sensitivity parameter combining the compositional and strength effects is proposed, and results from a large number of tests on commercial steels are shown to agree with it very well.